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INTERACTION OF SURFACE MAGNETOPLASMONS AND SURFACE OPTICAL PHONONS IN POLAR SEMICONDUCTORS

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13. ABSTRACT

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1.

INTERACTION OF SURFACE MAGNETOPLASMONS AND SURFACE OPTICAL PHONONS IN POLAR SEMICONDUCTORS

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Abstract

A theoretical investigation has been carried out of surface polaritons associated with surface magnetoplasmons coupled to surface optical phonons in polar semiconductors. The coupled mode frequencies are calculated for several orientations of the magnetic field relative to the surface and the direction of propagation in the large wave vector (unretarded) limit. Dispersion curves are calculated for the configuration in which the magnetic field is parallel to the surface and is perpendicular to the wave vector. Experimental possibilities for observing the interaction effects are discussed.

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1. Introduction

Several years ago, Yokota[1] and Varga[1] presented theoretical discussions of the interaction between bulk plasmons and bulk longitudinal optical phonons in polar semiconductors. Experimental observations of the coupled normal modes have been reported by Kaplan et al[2], Mooradian and Wright[2], and McMahon and Bell[2].

When a surface is present, excitations localized at the surface, such as surface plasmons[3] and surface optical phonons,[4] can occur. Surface polariton dispersion curves have been measured by Marschall, Fischer, and Quiesser[5] for surface plasmons and by Marschall and Fischer[6] for surface optical phonons. The surface excitation frequencies can also be determined by inelastic low energy electron scattering.[7]

The interaction of surface plasmons and surface optical phonons in polar semiconductors has been discussed by Kheifets,[8] by Chiu and Quinn,[8] and by Wallis and Brion.[8] Experimental studies bearing on this point have been reported by Alexander et al[9] and by Mirlin et al.[9] In the present paper we report the results of a theoretical investigation of magnetic field effects on interacting surface plasmons and surface optical phonons. A treatment of magnetic field effects on surface plasmons alone has been given previously by Brion et al[10] and by Chiu and Quinn.[11]

2. Theory

We consider a semi-infinite sample of polar semiconductor with free carriers in a simple parabolic energy band and separated from the vacuum by a planar surface defined by $x = 0$. An external magnetic field $\underset{\sim}{B}_o$ is taken to lie in the x-y plane and make an angle θ with the x-axis. The wave vector $\underset{\sim}{k}$ of the surface wave lies in the y-z plane and makes an angle ζ with the z-axis. The dielectric tensor can be written in the form

$$\epsilon_{ij} = \begin{pmatrix} \epsilon_1\sin^2\theta + \epsilon_3\cos^2\theta & (\epsilon_3-\epsilon_1)\sin\theta\cos\theta & -i\epsilon_2\sin\theta \\ (\epsilon_3-\epsilon_1)\sin\theta\,\cos\theta & \epsilon_1\cos^2\theta + \epsilon_3\sin^2\theta & i\epsilon_2\cos\theta \\ i\epsilon_2\sin\theta & -i\epsilon_2\cos\theta & \epsilon_1 \end{pmatrix} \quad (1)$$

where

$$\epsilon_1 = \epsilon_\infty\left\{1 + [\omega_p^2/(\omega_c^2 - \omega^2)] + (\omega_{LO}^2 - \omega_{TO}^2)/(\omega_{TO}^2 - \omega^2)]\right\},$$

$$\epsilon_2 = \epsilon_\infty\ (\omega_c/\omega)\omega_p^2/(\omega^2 - \omega_c^2),$$

$$\epsilon_3 = \epsilon_\infty\left\{1 - (\omega_p^2/\omega^2) + [(\omega_{LO}^2 - \omega_{TO}^2)/(\omega_{TO}^2 - \omega^2)]\right\},$$

$\omega_p^2 = 4\pi ne^2/m^*\epsilon_\infty$ and $\omega_c = eB_o/m^*c$ are the plasma and cyclotron frequencies, respectively, of the free carriers, and ω_{LO} and ω_{TO} are the long wavelength longitudinal and transverse optical phonon frequencies, respectively, n and m^* are the concentration and effective mass of the free carriers, and ϵ_∞ is the background dielectric constant. The quantity ϵ_3 is independent of magnetic field and is always the diagonal component parallel to the magnetic field when the latter is parallel to a Cartesian axis.

The first case to be discussed is that of no retardation, where one can introduce a scalar potential φ from which the electric field can be obtained using $\underset{\sim}{E} = -\nabla\varphi$. For a surface wave, we take

$$\underset{\sim}{E} = \underset{\sim}{E}_i^o \exp[-\alpha x + i(k_y y + k_z z - \omega t)], \qquad x \geq 0 \qquad (2a)$$

$$= E_e^o \exp[\alpha_o x + i(k_y y + k_z z - \omega t)], \qquad x < 0 \quad . \qquad (2b)$$

The displacement $\underset{\sim}{D} = \underset{\sim}{\epsilon}(\omega) \cdot \underset{\sim}{E}$ satisfies the equation $\nabla \cdot \underset{\sim}{D} = 0$, so that for a non-trivial solution,

$$\alpha^2 = (k_y^2 \epsilon_{yy} + k_z^2 \epsilon_{zz})/\epsilon_{xx} \quad , \qquad (3a)$$

$$\alpha_o^2 = k_y^2 + k_z^2 \equiv k^2 \quad . \qquad (3b)$$

The boundary conditions that the normal component of $\underset{\sim}{D}$ and the tangential components of $\underset{\sim}{E}$ be continuous at $x = 0$ lead to the dispersion relation(11)

$$\mathrm{sgn}\, \epsilon_{xx} [\epsilon_1^2 \xi^2 + \epsilon_1 \epsilon_3 (1 - \xi^2)]^{\frac{1}{2}} - \epsilon_2 \xi = -1 \qquad (4)$$

where $\xi = \sin\theta \cos\zeta$.

We have carried out specific calculations for several cases.

a. $\underset{\sim}{B}_o \perp$ surface

The decay constant is specified by $\alpha^2 = k^2(\epsilon_1/\epsilon_3)$, and the dispersion relation is given by $\epsilon_3(\epsilon_1/\epsilon_3)^{\frac{1}{2}} = -1$. We see that a surface wave can exist ($\alpha^2 > 0$) only if ϵ_1 and ϵ_3 have the same sign. Furthermore, the dispersion relation shows that ϵ_3 must be negative, so ϵ_1 must also be negative. In Fig. 1, we plot the frequencies for the coupled surface optical phonon-surface magneto-plasmon modes as functions of applied magnetic field for the situation where the zero field surface plasmon frequency, $\omega_{sp} \equiv \omega_p/[1 + (1/\epsilon_\infty)]^{\frac{1}{2}}$, is 0.8 of the surface optical phonon frequency, $\omega_{SO} \equiv [\omega_{TO}^2 + ((\omega_{LO}^2 - \omega_{TO}^2)/(1 + (1/\epsilon_\infty))]^{\frac{1}{2}}$. Also shown are the frequencies for the uncoupled modes. We note that the interaction forces the dispersion curves apart in the low field region and that the plasmon-like curve terminates at the line $\omega = \omega_c$. At this point, ω_c equals the smaller of the frequencies for which ϵ_3 is zero. To the right of the line $\omega = \omega_c$, the condition that ϵ_1 and ϵ_3 are both negative is no longer satisfied and no surface plasmon exists. The phonon-like mode also terminates at the line $\omega = \omega_c$, where ω_c is now equal to the higher frequency zero of ϵ_3. To the right of $\omega = \omega_c$, a second phonon-like branch starts at $\omega = \omega_{TO}$ and monotonically approaches the asymptotic value ω_{SO}. Thus, the phonon-like mode undergoes a discontinuity in crossing the line $\omega = \omega_c$.

A similar plot for the case $\omega_{sp}/\omega_{SO} = 1.2$ is shown in Fig. 2. The plasmon-like branch now lies above the phonon-like branch, but still terminates at the line $\omega = \omega_c$. The phonon-like branch again exhibits a discontinuity in crossing the line $\omega = \omega_c$. The discontinuity is in the opposite direction, however, from that found in the preceding case. The portion of the phonon-like branch to the right of the line $\omega = \omega_c$ is relatively insensitive to the value of ω_{sp}/ω_{SO}.

b. $\underset{\sim}{B}_o \parallel$ surface, $\underset{\sim}{k} \parallel \underset{\sim}{B}_o$

For this case, the decay constant is specified by $\alpha^2 = k^2(\epsilon_3/\epsilon_1)$, and the dispersion relation is given by $\epsilon_1(\epsilon_3/\epsilon_1)^{\frac{1}{2}} = -1$. Case b is qualitatively exactly the same as case a, and the same statements apply in both cases. Since both ϵ_1 and ϵ_3 must be negative, the dispersion relations, in fact, are identical. Figures 1 and 2 are therefore applicable to case b as well as to case a. One can write the squared decay constant and dispersion relation for both cases a and b in the common forms $\alpha^2 = k^2(\epsilon_k/\epsilon_{nor})$ and $\epsilon_{nor}(\epsilon_k/\epsilon_{nor})^{\frac{1}{2}} = -1$ where ϵ_k is the diagonal component parallel to $\underset{\sim}{k}$ and ϵ_{nor} is the diagonal component normal to the surface.

c. $\underset{\sim}{B}_o \parallel$ surface, $\underset{\sim}{k} \perp \underset{\sim}{B}_o$

The decay constant is simply given by $\alpha^2 = k^2$, and the dispersion relation is $\epsilon_1 - (\mathrm{sgn}\ k)\ \epsilon_2 = -1$. One sees immediately that this case is nonreciprocal - i.e., positive and negative wave vectors of the same magnitude are inequivalent. We do not have terminating branches as in cases a and b, since α^2 is no longer a function of ϵ_1 and ϵ_3. In Fig. 3, a plot is given of the coupled mode frequencies as functions of applied magnetic field for $\omega_{sp}/\omega_{SO} = 0.5$. The lack of equivalence of positive and negative wave vectors is clearly evident. The positive $\underset{\sim}{k}$ plasmon-like mode increases in frequency nearly linearly with field until it approaches ω_{SO}, where it bends over and becomes a phonon-like mode at large $\underset{\sim}{k}$. The phonon-like mode at small $\underset{\sim}{k}$ bends upward and becomes a plasmon-like mode at large $\underset{\sim}{k}$. The negative $\underset{\sim}{k}$ plasmon-like mode decreases in frequency and never approaches ω_{SO}, so the admixture of plasmon and phonon modes is rather small in this case. If we consider the situation shown in Fig. 4 for $\omega_{sp}/\omega_{SO} = 2.0$, we see that the roles of positive and negative $\underset{\sim}{k}$ are interchanged. The negative $\underset{\sim}{k}$ plasmon-like mode now interacts strongly with the phonon-like mode, whereas the positive $\underset{\sim}{k}$ plasmon-like mode does not.

We now turn our attention to the case where retardation is taken into account. For simplicity we restrict ourselves to the configuration $\underset{\sim}{B}_o \parallel$ surface, $\underset{\sim}{k} \perp \underset{\sim}{B}_o$. This situation (without phonons) has been treated by Chiu and Quinn[11] for $\epsilon_\infty = 1$ and by Brion et al[10] for general ϵ_∞. Brion et al found that a gap exists in the dispersion curve (ω vs. $\underset{\sim}{k}$) if the background dielectric constant ϵ_∞ and the cyclotron frequency satisfy the inequality $\epsilon_\infty > (\omega_c^2 + \omega_p^2)^{\frac{1}{2}}/\omega_c$. We now have a situation where a new relationship, that between ϵ_∞ and ω_c, has an important bearing on the results. The interaction between surface optical phonons and surface magnetoplasmons may be expected to lead to interesting effects if ω_{SO} is situated in the gap region. One way of viewing the situation is to regard ϵ_∞ as being a frequency-dependent quantity due to phonons. In the absence of phonons, ϵ_∞ arises from interband transitions and is relatively frequency-independent in the region of interest.

The results for the dispersion curves for $\underset{\sim}{k} > 0$ are displayed in Fig. 5. The interaction forces the upper and lower sections of the magnetoplasmon dispersion curve apart. In addition, the surface phonon dispersion curve splits into two branches. The lower branch starts at the light line at one of the zeros of ϵ_1 and quickly flattens out at its asymptotic value for large k. The upper branch starts at the light line at ω_{TO} and rises until it intersects a bulk dispersion curve, where it terminates. When $\underset{\sim}{k} < 0$, the surface phonon branch is a single branch starting at the light line at ω_{TO} and rising to an asymptotic value.

3. Experimental Considerations

The various interaction effects exhibited by the surface polariton dispersion curves discussed in this paper should be experimentally observable using either samples with a grating ruled on the surface[5] or attenuated total reflection.[6] Since high magnetic fields are required, either a Bitter magnet or a superconducting magnet will be needed. The simplest configuration is probably that of case b where $\underset{\sim}{B}_o \parallel$ surface and $\underset{\sim}{k} \parallel \underset{\sim}{B}_o$, but the other configurations should also be handleable.

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Figure Captions

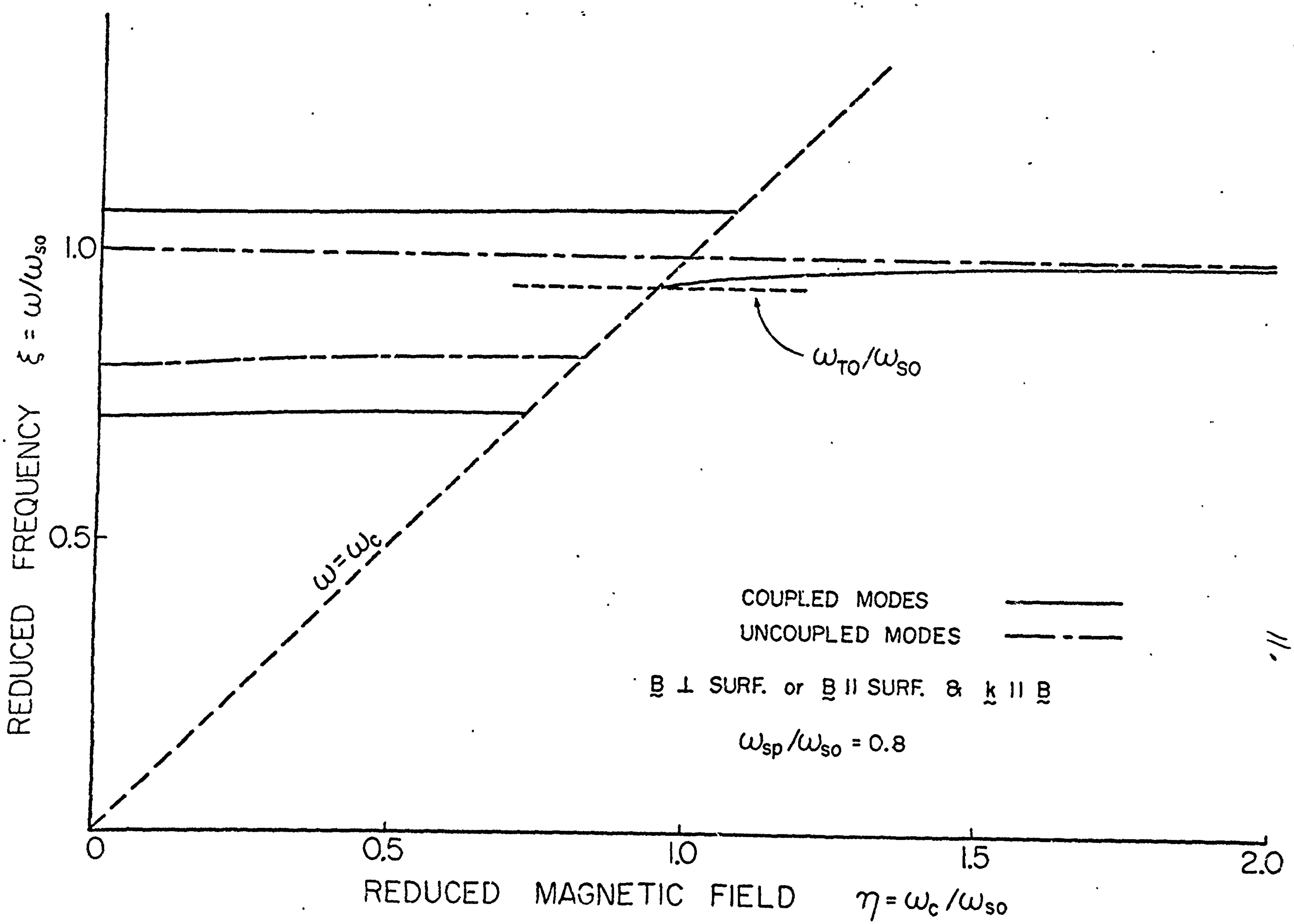
Fig. 1. Coupled mode frequencies (unretarded) in n-InSb plotted against applied magnetic field for $\underset{\sim}{B}_o \perp$ surface and $\omega_{sp}/\omega_{SO} = 0.8$.

Fig. 2. Coupled mode frequencies (unretarded) in n-InSb plotted against applied magnetic field for $\underset{\sim}{B}_o \perp$ surface and $\omega_{sp}/\omega_{SO} = 1.2$.

Fig. 3 Coupled mode frequencies (unretarded) in n-InSb plotted against applied magnetic field for $\underset{\sim}{B}_o \parallel$ surface, $\underset{\sim}{k} \perp B_o$, and $\omega_{sp}/\omega_{SO} = 0.5$.

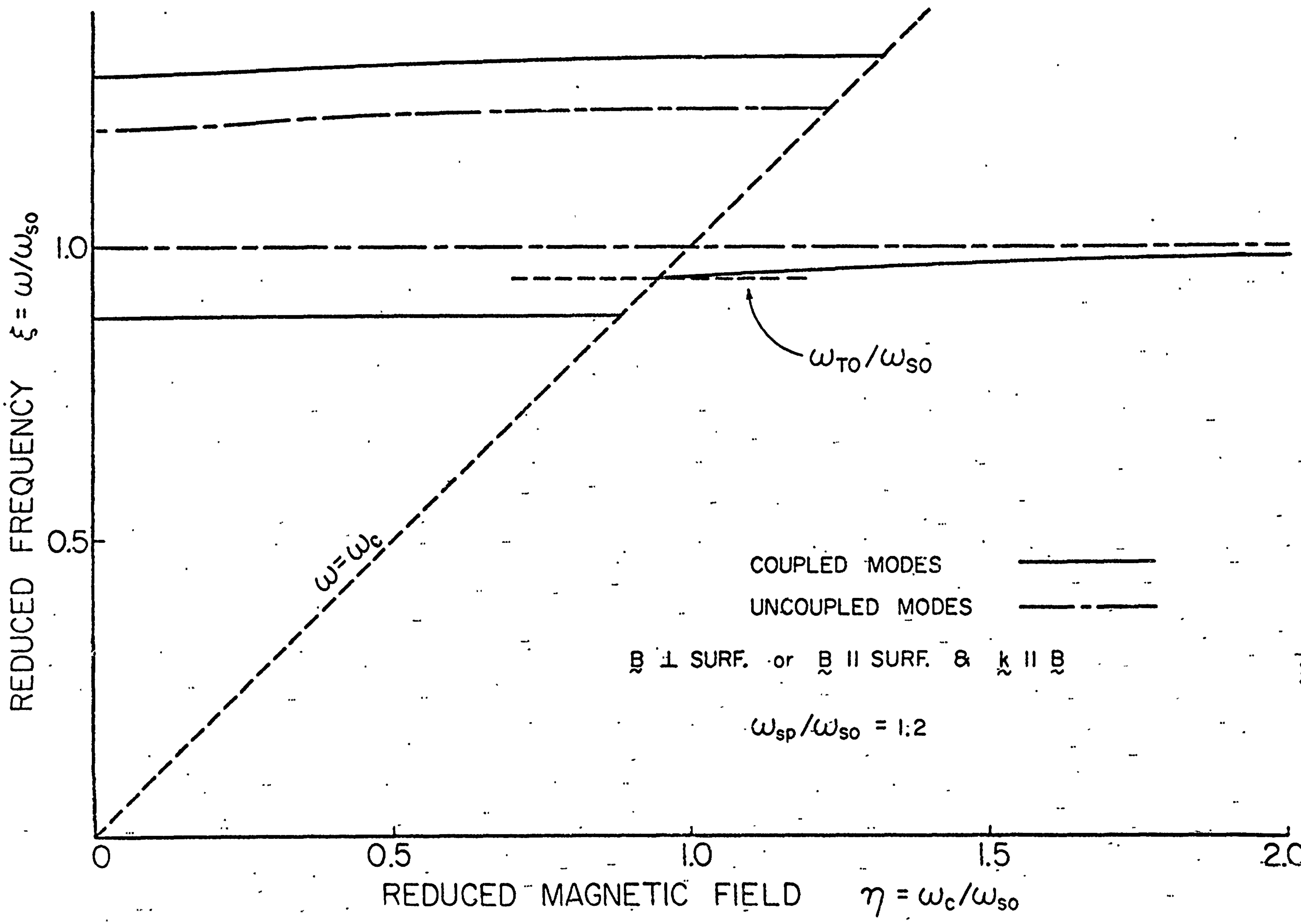
Fig. 4. Coupled mode frequencies (unretarded) in n-InSb plotted against applied magnetic field for $\underset{\sim}{B}_o \parallel$ surface, $\underset{\sim}{k} \perp \underset{\sim}{B}_o$, and $\omega_{sp}/\omega_{SO} = 2.0$.

Fig. 5. Dispersion curves for n-InSb for $\underset{\sim}{B}_o \parallel$ surface, $\underset{\sim}{k} \perp \underset{\sim}{B}_o$, and $\omega_{sp}/\omega_{SO} = 1.0$.

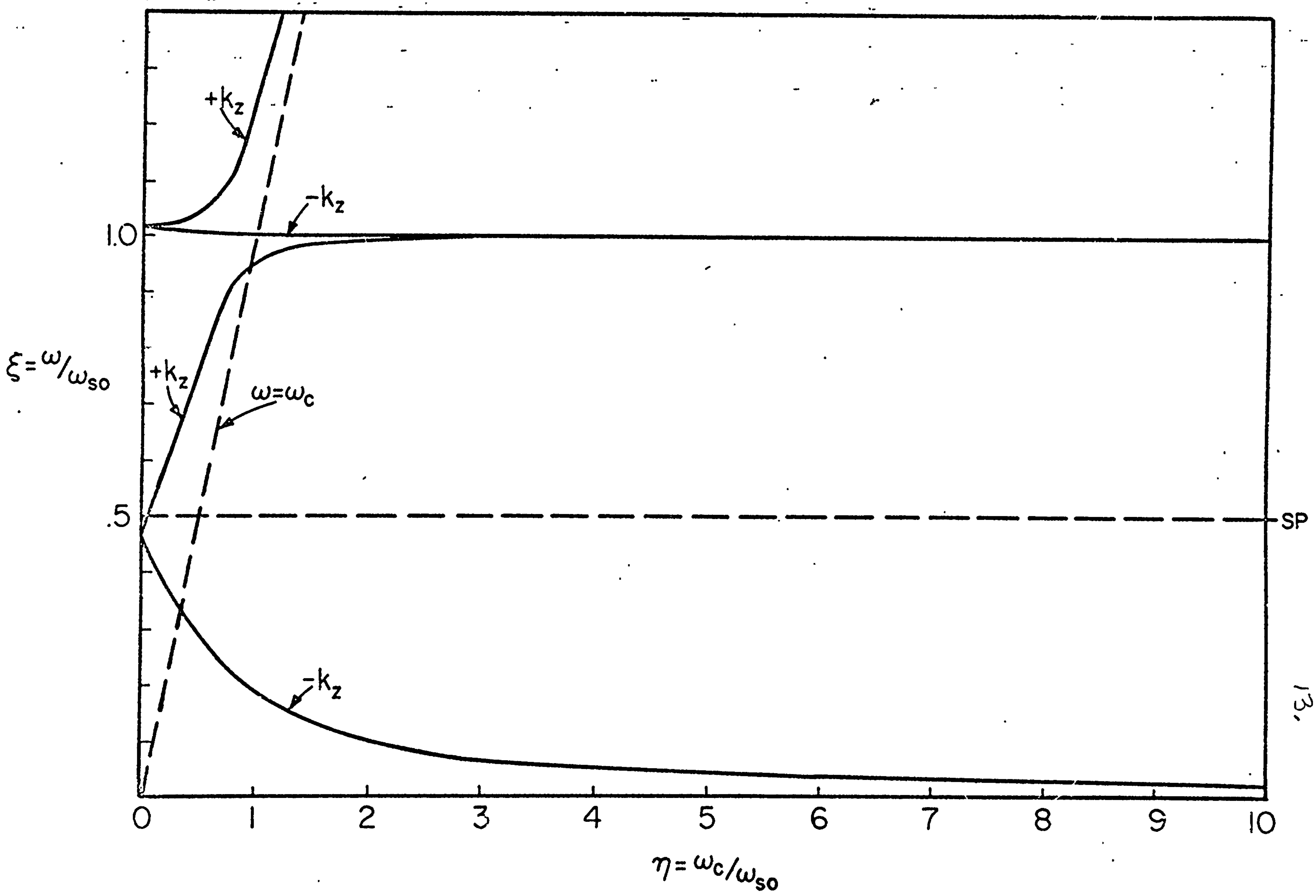


REDUCED FREQUENCY $\xi = \omega/\omega_{so}$
1.0
0.5
0
0.5
1.0
1.5
2.0
REDUCED MAGNETIC FIELD $\eta = \omega_c/\omega_{so}$
$\omega = \omega_c$
ω_{TO}/ω_{so}
COUPLED MODES
UNCOUPLED MODES
$\underset{\sim}{B} \perp$ SURF. or $\underset{\sim}{B} \parallel$ SURF. & $\underset{\sim}{k} \parallel \underset{\sim}{B}$
$\omega_{sp}/\omega_{so} = 0.8$

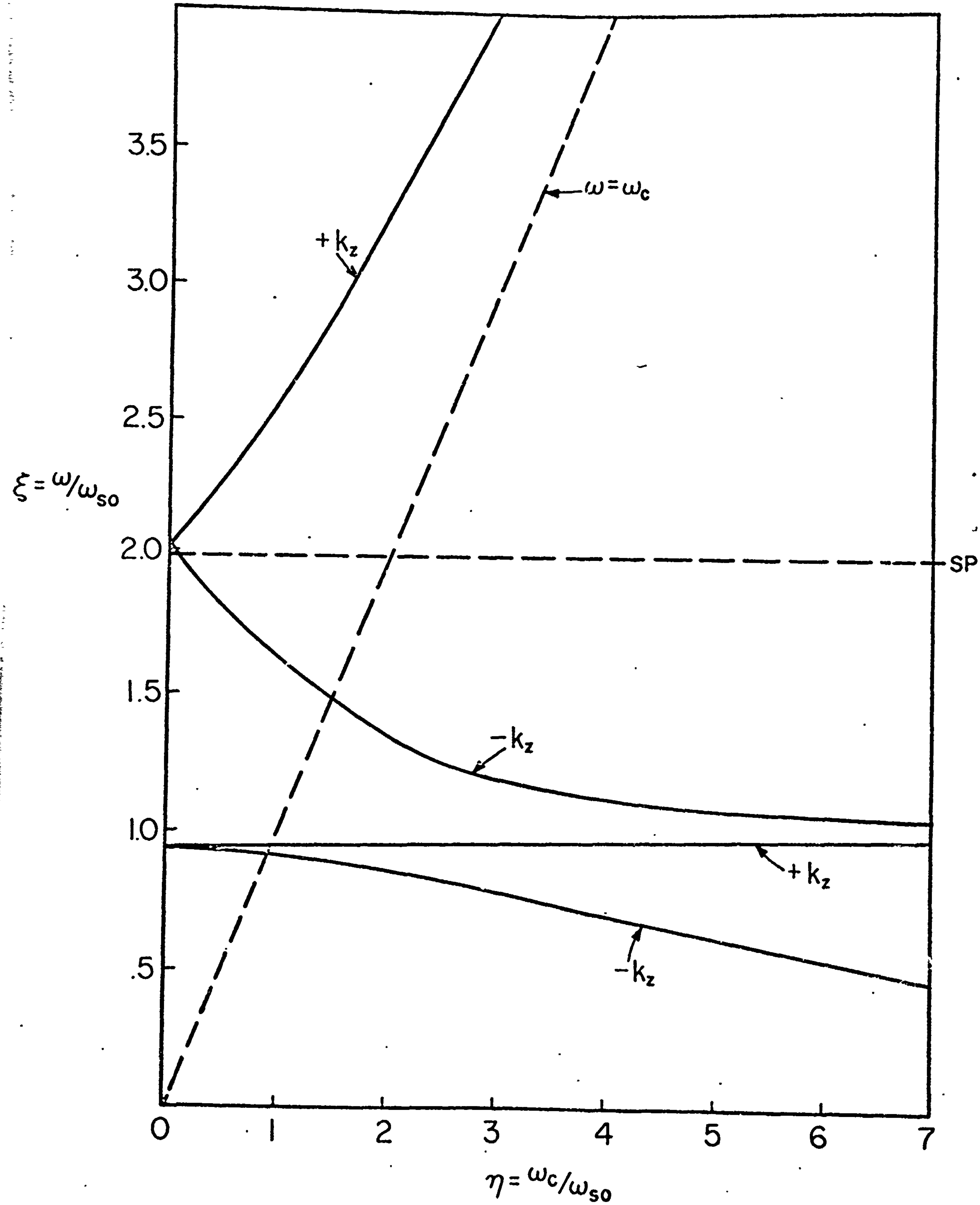
12a



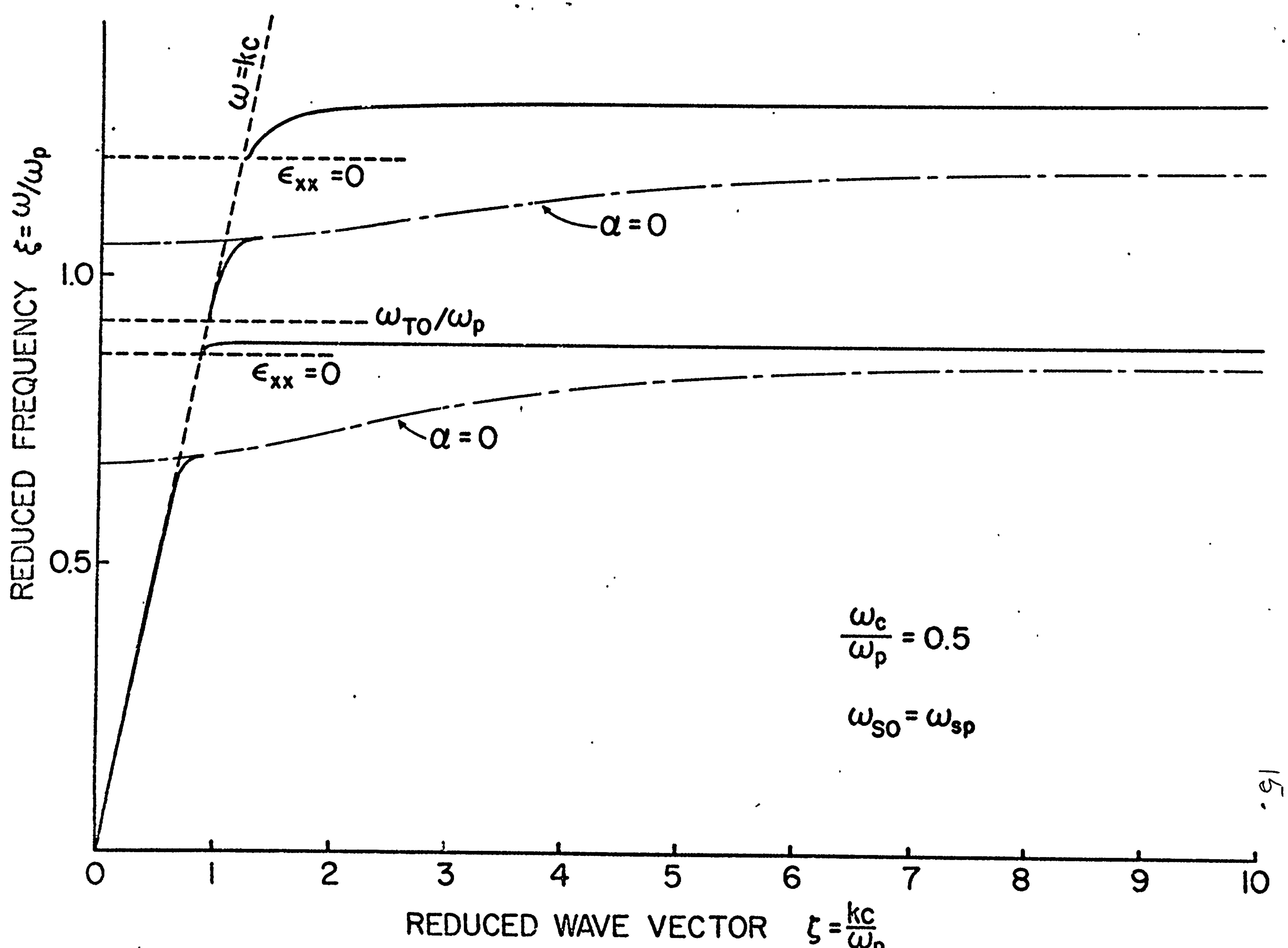
REDUCED FREQUENCY $\xi = \omega/\omega_{so}$
1.0
0.5
ω_{TO}/ω_{SO}
$\omega = \omega_c$
COUPLED MODES
UNCOUPLED MODES
$\underset{\sim}{B}$ ⊥ SURF. or $\underset{\sim}{B}$ ∥ SURF. & $\underset{\sim}{k}$ ∥ $\underset{\sim}{B}$
$\omega_{sp}/\omega_{so} = 1.2$
0
0.5
1.0
1.5
2.0
REDUCED MAGNETIC FIELD $\eta = \omega_c/\omega_{so}$



$+k_z$
$-k_z$
1.0
$\xi = \omega/\omega_{so}$
$+k_z$
$\omega = \omega_c$
.5
SP
$-k_z$
0
1
2
3
4
5
6
7
8
9
10
$\eta = \omega_c/\omega_{so}$



3.5
3.0
2.5
2.0
1.5
1.0
.5
$\xi = \omega/\omega_{so}$
$+k_z$
$-k_z$
$+k_z$
$-k_z$
$\omega = \omega_c$
SP
0
1
2
3
4
5
6
7
$\eta = \omega_c/\omega_{so}$


REDUCED FREQUENCY $\xi = \omega/\omega_p$
1.0
0.5
0
1
2
3
4
5
6
7
8
9
10
REDUCED WAVE VECTOR $\zeta = \frac{kc}{\omega_p}$
$\omega = kc$
$\epsilon_{xx} = 0$
$\alpha = 0$
ω_{TO}/ω_p
$\epsilon_{xx} = 0$
$\alpha = 0$
$\frac{\omega_c}{\omega_p} = 0.5$
$\omega_{SO} = \omega_{sp}$